REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 1998	Final Report

4. TITLE AND SUBTITLE

Feasibility Study of a 3D Optical Storage System

5. FUNDING NUMBERS

F6170898W0017

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
PSC 802 BOX 14
FPO 09499-0200

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

SPC 98-4010

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

A

13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking Technical University of Budapest as follows: The contractor will investigate the comparative evaluation of different optical-system architectures from the point of view of functional parameters (capacity and speed) as well as determination of requirements, specification and technical feasibility of optical, mechanical and electronic subsystems.

14. SUBJECT TERMS

EOARD, Optical Memory, Optical Components, Optical Diagnostics

15. NUMBER OF PAGES

20

16. PRICE CODE

N/A

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19, SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

AQF99-04-0501

Feasibility Study of a 3D Optical Data Storage System

Final Report

Contr.No.F 61708-98-W0017

November 1998

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Abstract

High (~1Tb/cm3) capacity 3D optical data storage systems based on two photon excitation were evaluated. Previously proposed systems were shown to suffer from low I/O bandwidth rates. We propose a new serially addressed system based on thick storage layer optical disc format and acousto-optic addressing that can combine 1TB/disc capacity with 100 Mb/s I/O bandwidths. For replacement of the bulky Ti:Sapphire laser considered before a compact fiber laser is recommended as light source.

1. Evaluation of two-photon 3D optical data storage architectures

Application of two photon excitation for 3D optical date storage has been demonstrated. [1-6] Advantage of the technique is due to the extremely high potential data storage density. It is achieved by the non-linear response of the storage material that makes transmission of light beams through the storage material possible except in remotely designated regions, where high photon density of one or two light beams induces two-photon absorption.

Since the 3D spatial resolution in optics is limited by diffraction to the order of magnitude of the wavelength the space required to store 1 bit is in the order of 1 μm^3 allowing data storage densities exceed 1 Tb/cm^3.

A number of synthetic photochromic materials applicable for two-photon 3D optical data storage have been developed and investigated.[5] The mechanism of writing the

information is 2-photon excitation while reading is carried out at lower intensity by fluorescence.

Applicability of the two photon 3-D data storage is determined by the accessibility of the enormous amount of information that can be potentially stored, i.e. I/O bandwidth. With storage capacity in the Tb range, I/O in the range of 100Mb/s rates would be desirable. This would allow about 3 hours playing/recording time. Input rates are usually more demanding since writing requires more energy than reading.

Two basic architectures have been proposed.

1. Page-oriented parallel writing and reading has been worked out by P.Rentzepis' group at the U. of California in Irvine. [4,5,7]

   The scheme of their arrangement is shown in Fig.1.

   The 1.06 μm wavelength light is used for information beam and its frequency doubled 532 nm part for addressing. The parallel information input is through a spatial light modulator, modulating the information beam, and for parallel readout by the addressing beam, a camera is used. It requires a dynamic focusing system for feeding the information into consecutive planes, and a scanning anamorphic optical system for page addressing. The storage material is SP+PMMA.

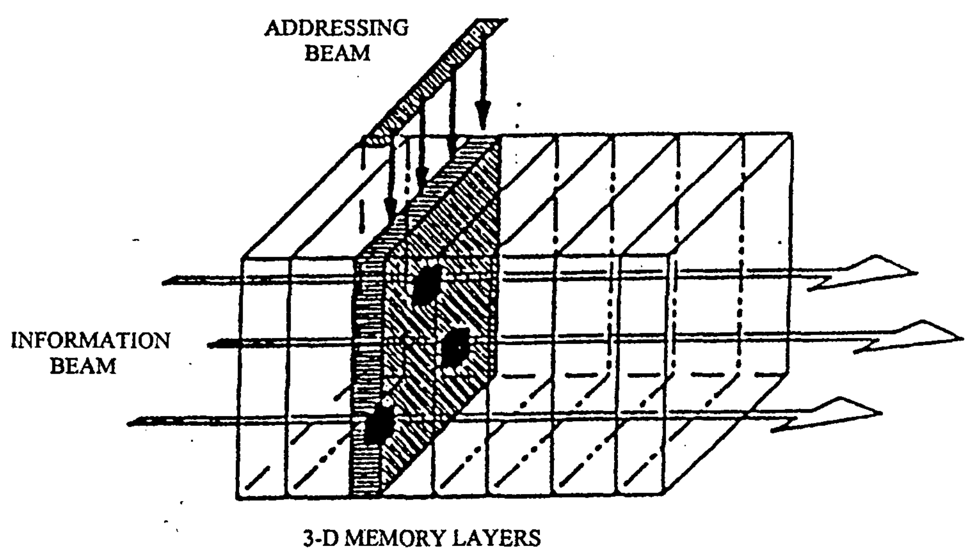

Fig.1.

In their recent experiment the laser operated f_{rep}=10Hz repetition rate with τ_{pulse}=30 ps pulses. 9mm^2 pages were generated, that can potentially store $9 \cdot 10^6$ bits but the

actual number of pixels was 10^4, 30 μm x 30 μm size each. It was written at $\overline{P} = 3.5\frac{W}{cm^2} = 3.5 \cdot 10^{-5}\frac{mW}{\mu m^2}$ average power density level with 240 sec exposure time (2400 pulses). This would correspond to a potential 38 kb/s bandwidth if 1 μm x it 1 μm pixel size was used. In this experimental system the addressing beam was 80 μm wide. If the latter was focused to a 1 μm sheet of light (corresponding to the 1TB/cm^3 data density) an increase in bandwidth due to the increased addressing photon density and consequently decreased exposure time (3sec, 30 pulses) could be achieved up to 3Mb/s. Further improvement would require increase of average laser power $\overline{P}$.

The bandwidth can increase with the square of the pulse energy - due to the non-linear nature of absorption, but only linearly with the pulse repetition frequency.

However the main technical limitation at this time seems to be realization of the dynamic focusing lens and the high resolution anomorphic addressing telescope that would make the 1 μm^3 pixel sizes available.

Page oriented parallel writing and reading has also been proposed by colliding counter propagating pulses [4]. However due to the fact that pulses even as short as 100 fs coincide at a length of about 20μm in the material, the high data density would be lost when this technique was used.

2. Serial writing and reading has been proposed by P.Prasad's group at SUNY in Buffalo [6,8]. Their arrangement is shown in Fig.2.

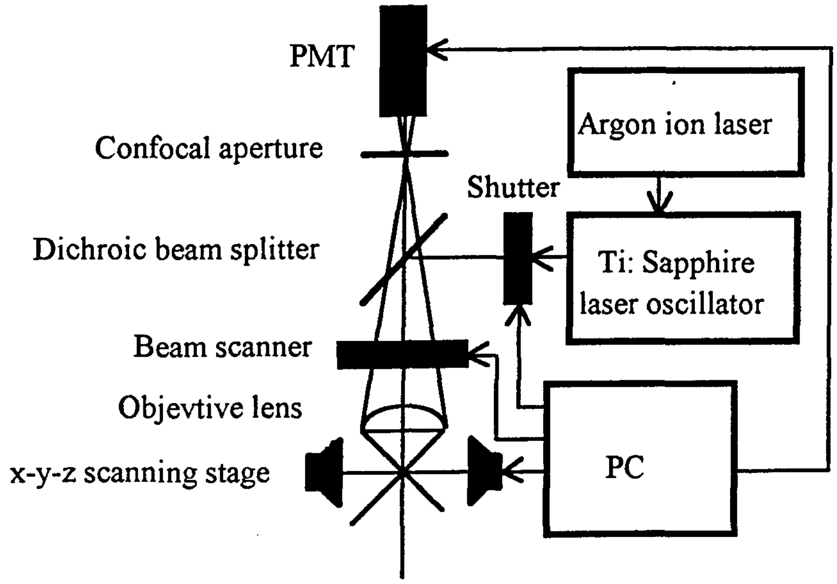

Fig.2.

The light source is a Ti:Sapphyre mode locked laser at λ=798 nm, with f_{rep}=100MHz and τ_{pulse}=100fs. The storage material is APSS+HEMA that is transparent for the infrared light but shows two-photon absorption at high photon density. The information is fed serially bit by bit through a scanning confocal microscope with a lateral resolution better than 1 μm^2. An inter-plane spacing of 5μm was demonstrated for 40 planes. Average writing power was $\overline{P} = 15mW/\mu m$ with 1μsec exposure time (100 pulses) per pixel (i.e. bit). This would correspond to 1Mb/s writing speed. A 10 fold increase in the peak power of pulses would allow 10nsec exposure time corresponding single pulse writing and reaching 100 Mb/s I/O bandwidth that seems to set an upper limit for this technique at present. Addressing is carried out by mechanical scanning that limits the bandwidth to 1-2 Mb/s at reasonable mechanical velocities (1-2 m/s).

In summary one can say that applicability of the Tb/cm^3 storage capacity of 2 photon 3D optical data storage is limited at present by the lack of appropriate I/O and addressing methods that would enable I/O bandwidths reach rates up to 1Gb/s.

2.1. Architecture for high speed serial 3D 2 photon optical data storage.

In Section 1. parallel and serially addressed 3D optical data storage systems based on two photon excitation were investigated. It was found that application of the

potential high storage density (>1TB/cm^3) is hindered by low (1-3 Mb/s) I/O bandwidths that have been achieved up to now.

We propose that much higher bandwidths can be realized for the serially addressed system if optical routing is used for addressing.

Since fully mechanical addressing is out of question due to the extreme kinematic requirements other techniques were investigated. Optical routing switches using waveguide technologies had to be omitted due to predicted nonlinear interactions of the 100 fs pulses in the waveguide.

Therefore application of free space deflectors was chosen and details of this system will be presented in the following.

In order to reach full capacity of the 100 MHz repetition rate laser source, 3D data storage in a disc format is proposed as shown in Fig 3.

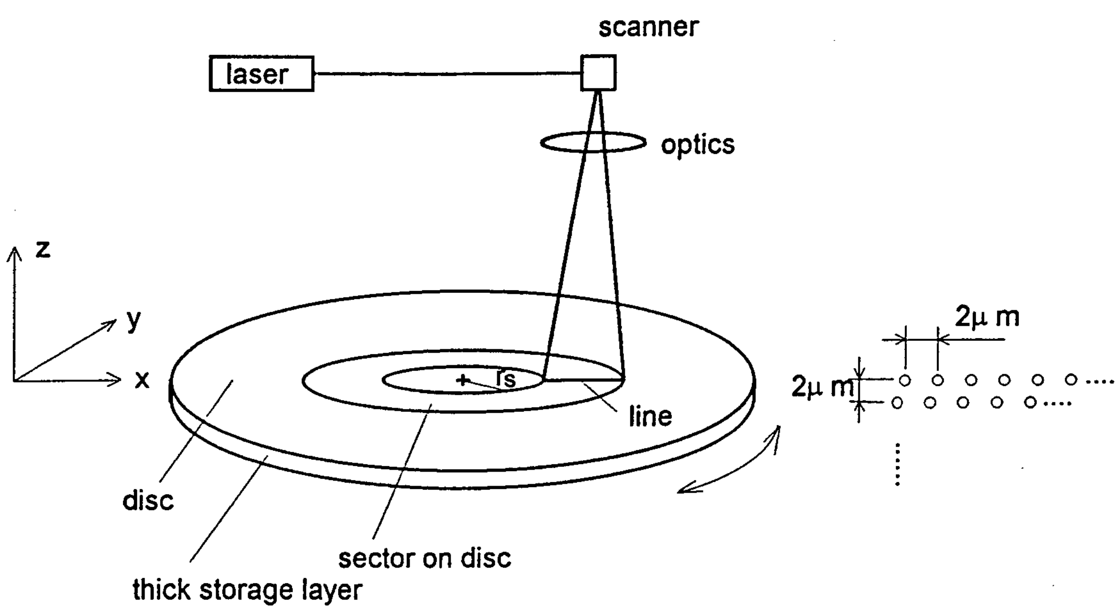

Fig.3.

The laser spot is moving with high speed along a single line in the x direction parallel to the disc surface, driven by the scanner.

The scanner with the appropriate optics generates about 500-1000 pixels along the line during 5-10 μs. Centers of the pixels are at a distance of w=2μm of each other. During this time the disc has to move also 2 μm in the y direction. This corresponds to 0.2 m/s rotational velocity. A typical sector at radius r_S consists of 2 $r_S\pi/w$ lines therefore $(2r_S\pi/w)\cdot 500$ to 1000 pixels. I/O time for a full sector is $(2r_S\pi/w)\cdot 5$-10μs. E.g. on the

2mm wide sector of r_s=50mm $157 \cdot 10^6$ pixels (157 Mb), can be accessed in 1.57 sec corresponding to 100 Mb/s.

Sectors can be arranged concentrically and different sectors can be reached by mechanical motion of the optical head relative to the center of the disc. Width of a sector is 1-2 mm. Switching between adjacent sectors with $10\frac{mm}{s}$ relative linear velocity in the radial direction allows 100-200 ms switching time. Another option is arrangement in a spiral form allowing continuous access of a complete layer on the data storage disc. Typical radial velocity of the optical head is in the range 1-2 mm/sec.

On one layer the amount of information stored is 2.5 Gb with w=2μm pixel distance, that can reach 10 Gb with 1 μm pixel distance. Reducing pixel distance is feasible due to the nonlinear nature of the light-material interaction. Namely if 2 μm width can be provided for the light intensity distribution in the focal range the 2 photon interaction is expected to occur in a 1μm wide region. Exact size depends on the storage material and light intensity, and needs to be experimentally investigated.

In case of 100 different layers on top of each other data capacity of a CD format disc can reach 1 Tb.

The servo system is based on the same principles as those used in present day optical disc drives.

Since the distance between consecutive layers can be 5μm, maximum distance between layers would be 0.5mm that can be accessed in 50ms with maximum $10\frac{mm}{s}$ relative linear velocity between the disc and the optics in the z direction perpendicularly to the disc, that is mechanically feasible. Selection of the required layers can be accomplished with a servo system based on presently used solutions in optical memory devices.

In summary the architecture outlined above provides I/O bandwidth of 100 Mb/s that corresponds to the repetition rate of the light source in a disc format requiring mechanically feasible movements (velocities).

The most critical issue is the high speed scanning optical system that should provide

- sector width: 1-2 mm
- focal spot size ≤2μm

- scan speed: 1 pixel/10ns
- depth of field < 5µm
- range of focus 0.5 mm in the z direction
- good efficiency

3. High speed, high resolution scanning

After evaluating of a number of different approaches an acousto optic deflector was chosen for scanner.

Criteria of selection is the simultaneous demand for high resolution, scan speed and efficiency. On this basis LND-250-100 deflector of Brimrose was found as optimum: nominal resolution N_o=1000 spots, access time τ=1µs and maximum diffraction efficiency η=20%. Performance of this $LiNbO_3$ deflector can be estimated as follows:

During a full scan the driving frequency is swept from 2GHz to 3GHz during the scan time T. Since the pulses follow in 10ns intervals, the number of individual shots during a scan period is $N = \frac{T}{10ns}$. On the other hand, since the access time of the deflector is τ=1µs, in order to avoid angular overlap of the deflected pulses $N = \left(1 - \frac{\tau}{T}\right) N_o$ is the dynamic resolution of the device. From this, the scan time T can be determined. For this deflector T=8.9µs and N=890 must be chosen to ensure the 100 Mb/s data rate.

This slightly decreases the amount of data stored in a sector on the disc (89% of that outlined before) but the geometrical size decreases by the same amount, so the data density is unchanged, only the rotational velocity must be increased by 11%.

Very significant problem is, however, the peculiar properties of the optical beam emerging from the deflector. To start with, due to the fact that the active aperture of the deflector is 0.07x3.5mm, it must be illuminated by a highly astigmatic beam. On the other hand, due to the rapid frequency sweep in the plane of the deflection the deflector behaves like a cylindrical lens.

The angle of convergence is $\Delta\varphi = \frac{\lambda}{\upsilon} \Delta f$ where λ is the optical wavelength (800nm) υ is the acoustic velocity in the crystal due to the frequency sweep:

$1GHZ \cdot \frac{\tau}{T} = 112.3\ MHz$. With these data Δφ=25.9 mrad that corresponds to a cylindrical focal length $f_c = \frac{3{,}5mm}{\Delta\varphi} = 134mm.$

The total deflection angle at λ=800nm is $\Delta\alpha = \frac{800nm}{630nm} 10^{\circ} = 12.7^{\circ}$ taking into account the nominal 10° for λ=630nm.

In conclusion the acousto-optic deflector selected can fulfil the speed and resolution requirements. However, further investigation is necessary of the appropriate optical system to focus each laser pulse with the desired optical quality onto the storage material.

The optical system

In the case of the 3D optical memory the information bits are distributed in a volume, embedded in a special material with a given refractive index. For addressing the bits a volumetric scanning optical system is needed. Along the tree coordinate axis access times are different. In the x direction for the fastest scanning a one dimensional AO deflector is used. The storage medium (disc) rotates in y direction. In the z direction the slowest access is provided by relative mechanical motion of the disc and the optical system.

Design consideration of the main elements of the system

From the optical point of view there are four difficulties:

- focusing the laser beam into a sharp astigmatic line required by the AO deflector, and after the crystal reshaping it to a circular beam,
- to compensate the cylindrical lensing effect caused by the fast scanning in the AO crystal,
- scanning in the storage layer in different depths corresponding to variable optical thicknesses,
- adjusting the AO deflector into the scanning lens.

The design of the optical system consists of four main parts: cylindrical lenses to create the astigmatic beam, compensating cylindrical lens, Fθ objective, and adjusting optics.

Cylindrical lenses

The selected AO deflector is chosen to be used at a resolution of 500 spots that somewhat reduces the required astigmaticity of the beam entering the deflector. The responding optical window (active aperture) of the fast AO deflector is 2.3x0.076mm. This means, that the circular beam from the laser has to be focused to a sharp line into the AO deflector crystal with a cylindrical lens, and after the crystal the scanned line has to be reshaped into a diffraction limited scanned circular plane beam. The input and output beam diameters are 2.3 mm. The focal lengths of the cylindrical lenses have to be shorter than 72mm. (In this case the diffraction width of the focal line will be less than the width of the optical window of the AO deflector.) The focusing and reshaping of the beam is realized with an optimized confocal cylindrical optical system. (See lenses CL1. and CL3. in Fig.4.)

Compensating cylindrical lens

The AO deflector scans $\Delta\alpha=12.75^{\circ}$. In order to accomplish the required fast scanning it is necessary, that the crystal be fed with a continuously varying frequency acoustic wave.

The cylindrical lensing action of the crystal has to be compensated with a cylindrical lens with nearly equal focal distance and opposite sign, placed closely before or after the AO crystal. (See lens CL2. in Fig.4.)

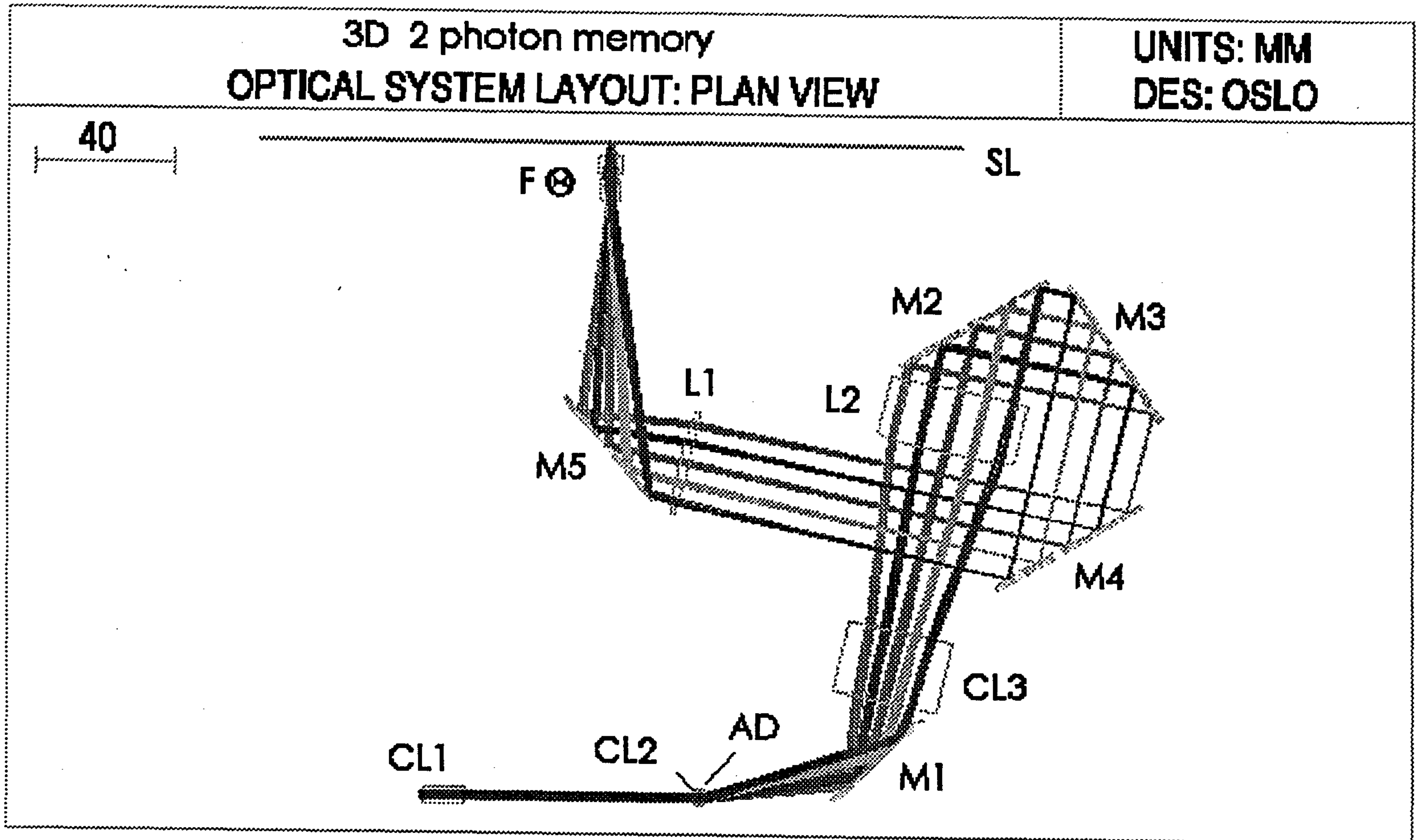
3D 2 photon memory
OPTICAL SYSTEM LAYOUT: PLAN VIEW
UNITS: MM
DES: OSLO
40
SL
F ⊖
M2
M3
L1
L2
M5
M4
CL3
AD
CL1
CL2
M1

Fig.4.

FΘ objective

Conventional scanning objectives, called FΘ objectives, scan a laser beam at a single line in a given plane. In our case the FΘ objective has to provide the possibility of scanning in different depths i.e. in a rectangle fraction of a the XZ plane, with 1x0.5mm dimension. From an optical point of view all points of this rectangle are different, because of the asymmetric behaviour of the deflector, and because of the varying layer thickness above the storage layer to be addressed.

Our calculations showed, that a relatively simple FΘ objective can be reoptimised for the different depths. In this case symmetric scanning system was used. We suppose that the memory layers are under a 0.8 mm cover layer, and the memory layer thickness is 0.5 mm. The refractive indices of the memory material and the cover layer are equal. (See Fig.5.). A planparallel plate causes spherical aberration and coma in a focused, scanned beam. To compensate this aberration at the whole rectangle a three element objective was designed (see FΘ objective in Fig.4.).

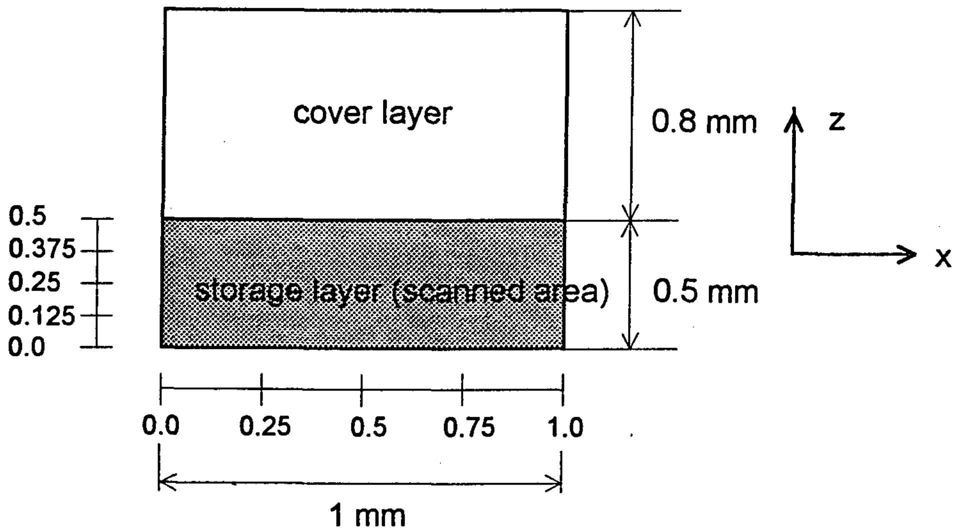

Fig.5.
The cover and storage layers, and the scanned area

Adjusting optics

For scanning the 1 mm sector width with 12.75° scanning angle a lens with f=4.5 mm focal length is needed. The scanner has to be at the entrance pupil of the FΘ objective. This is before the lens at a distance in the order of the focal distance. On this

short distance it is not possible to reshape the scanned beam into circular diffraction limited beam. This required adjusting the scanned beam into the FΘ objective, that was solved by using a simple 4f system. This consists of two confocally arranged lenses. At the first focal plane of the first lens is the AO deflector, and the second focal plane of the second lens is the entrance pupil of the FΘ lens. (The second focal plane of the first lens, and the first focal plane of the second lens are coincident.) This arrangement is simple, but long. For reducing size the optical path was folded. (The lenses L1, L2 constitute the 4f optical system, and M1, M2, M3, M4, M5 are folding mirrors in Fig.4.)

Design and analysis of the complete system

For the design, optimization, and analyse of the system the OSLO lens design program (ver. 5.2.) was used. The solid model of complete optical system is shown in Fig.6.

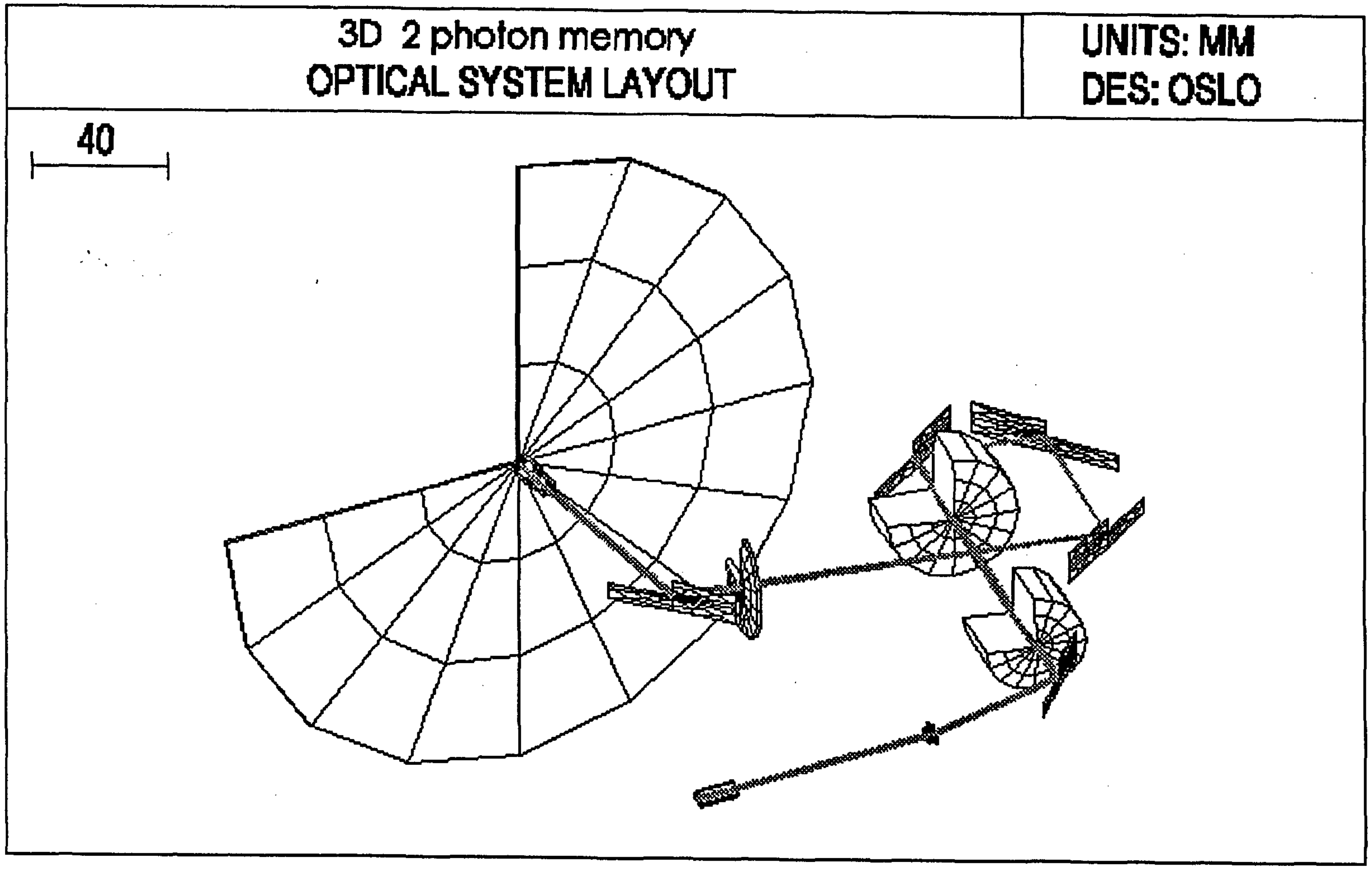

Fig.6.
The solid model of the complete optical system

The AO deflector was modelled with a diffractive optical surface, embedded in a $LiNbO_3$ material. The phase of the diffractive surface $\Phi(x)$ is varied along the x direction at the optical aperture of the crystal, with following equation:

$$\Phi(x) \approx C_1 x + C_2 x^2$$

The C_1x linear term describes deflection of the beam, and the C_2x^2 quadratic term the cylindrical lensing effect, where C_1, C_2 are two parameters. For different scanning angles appropriate values of C_1 where chosen. For modelling and optimization of system five different C_1 values were used i.e., the system was calculated at five different scanning angles.

For complete characterization of the system 25 configurations were used, namely: five different scanning angles, and for each angle five different depths in the storage layer. The storage layer depth difference was compensated by the air space thickness between the cover layer and the final lens of the FΘ objective.

After the optimization procedure diffraction limited beam quality was achieved for all 25 points. Fig 7. shows 25 diffraction spots arranged proportionally along the scanned rectangle. The radii of the spots are 2μm.

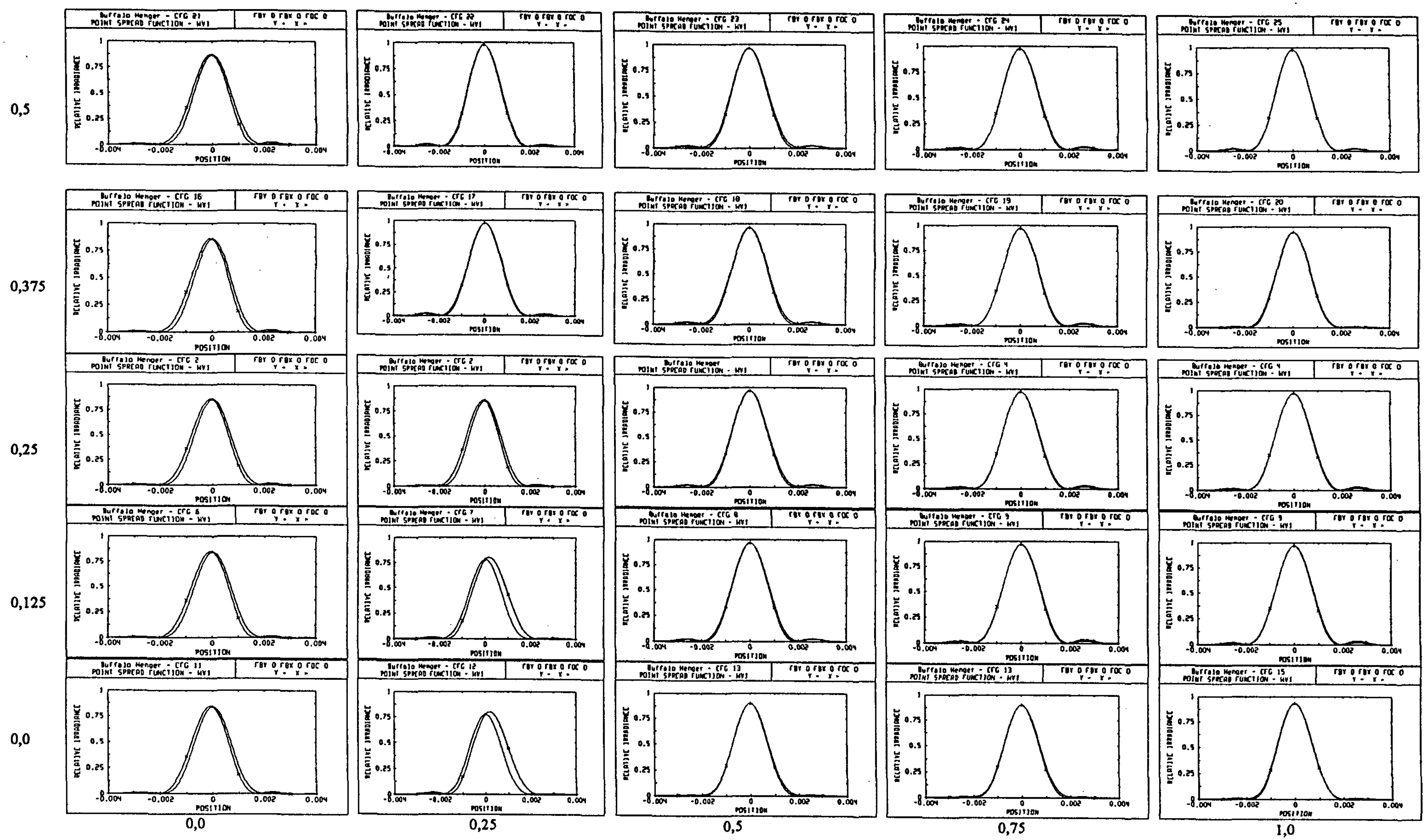

Fig.7.
Calculate relative diffraction intensity distribution in 5 lateral x 5 depth positions in the storage layer

4. The light source

The most serious criticism against serially addressed architectures for 3D 2 photon optical data storage architectures was the need for bulky Ar^+ laser pumped Ti: Sapphyre laser as light source.

The requirements for the laser are high peak power for efficient 2 photon excitation, high repetition rate to allow fast scanning, and relatively low average power in order to avoid destruction of the material. The high peak power is provided by the sub-picosecund mode-locked laser pulses. However if we consider that such pulses have quite a broad spectrum (100fs≡8nm, 10fs≡80nm) that suffer severe broadening upon travelling through dispersive optical elements it is clear that it is no use to shorten the pulse below 100fs, where the pulse broadening is expected to be 20-30%. [9]

The other limitation concerns the repetition rate. Since the fluorofore used for the 2 photon data storage typically have fluorescence lifetimes in the range of a few nanoseconds, in order to provide reasonable time resolution for the excited pixels pulse repetition time of not less than 10 ns is required, that limits repetition rate to 100 MHz. [9]

The mode-locked Ti: Sapphyre lasers can perform at these parameters in the range of tens of milliwatts of average power. However their size and complexity forbids their use in practical systems.

Recently mode-locked Erbium-doped fiber laser systems have been developed that are compact, user friendly and could provide excellent source for this application. [10]

Rare earth doped fibers are well suited for ultrafast applications due to their amplification bandwidth (6 THz) which is broad enough to support pulses even shorter than 100 fs. Dispersion problems can be solved by using appropriate fibers. The attractive feature of these lasers is their small size and robustness.

At present these lasers have reached the market, e.g. the Femtolite laser by IMRA which produces pulses shorter than 180 fs at 780 nm with 50 MHz repetition rate. [11]

Its size is 193x109x82 mm (Fig.8.)

of Prasad, and a hypothetical Ti:Sapphyre system that would allow 100 MHz I/O rate operation by single pulse writing are listed.

Table

	Prasad Ti:Sapphire	Single pulse writing Ti:Sapphire	Femtolite	Optimized fiber laser
λ	798	798	780	780
f_{rep}	100 MHz	100 MHz	50 MHz	100 MHz
T_{rep}	10 ns	10 ns	20 ns	10 ns
τ_{pulse}	100 fs	100 fs	180 fs	180 fs
t_{exp}	1 μs	10 ns	20 ns	10 ns
P_{peak}/pixel= $=\overline{P}\cdot\frac{T_{rep}}{\tau_{pulse}}$	1,5 kW	15kW	$\frac{15kW}{\sqrt{1,8}}=11kW$	11 kW
$\overline{P}/pixel$	$\overline{P}=1mW$	150 mW	100 mW	50 mW

Femtolite parameters shown in the 3rd coloumn would allow 50 MHz operation, however it, would require more than 100mW average power contrary to the presently available 10 mW. Since doubling the repetition rate is desirable to achieve the 100 MHz I/O rate that would reduce the estimated average power requirement to 50mW. (See last column in Table.)

Fortunately recent developments in mode locked fiber laser, like

- using cladding pumped fiber lasers
- using chirped pulse amplification, and
- using lithium niobate frequency doubling crystal with chirped poling period allowed boosting the average power over 300 mW at 780 nm. [9]

Increasing the repetion rate can be achieved by using shorter laser resonator. This can be realized without sacrificing power by improving the pumping efficiency using erbium/ytterbium co-doped amplifier fibers.

It is also worth noting that very recently repetition rates of up to 2.6 GHz have been demonstrated in mode-locked fiber lasers although average power was limited to 1.6 mW. [12]

5. Summary

We carried out a critical evaluation of previously proposed 3D 2 photon optical data storage architectures. Although the potential of very high data capacity (1Tb/cm^3) is very attractive low I/O bandwidths seriously limit applicability of these systems. Considering that 2 photon excited fluorescence lifetimes are in the range of a few nanoseconds, repetition rates up to 100 MHz are in principle feasible. However this requires an architecture providing high speed addressing and an appropriate light source.

In the course of this work we proposed a mutilayer (~100) optical disc format and combination of high speed optical scanning with feasible mechanical motion, that according to our calculations can perform 1 Tb/disc capacity with 100 Mb/s I/O rates. For the light source a compact mode locked fiber laser can be used.

Since most of the elements that we considered are commercially available we recommend that in the course of an experimental feasibility study a laboratory demonstrator of the system be built.

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